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To link to this article: https://doi.org/10.1081/PLN-120018573

Published online: 20 Aug 2006.

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Salinity and Irrigation Method Affect Mineral Ion Relations of Soybean

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ABSTRACT

Soybean [Glycine max (L.) Merrill] is moderately salt tolerant, but the method of irrigation used for crop production under saline conditions may influence the uptake and distribution of potentially toxic salts. This field study was conducted to determine the effects of application of saline waters by different methods, namely, drip and above-canopy sprinkler irrigation, on the ion relations of soybean cultivar “Manokin”. Salinity was imposed by adding NaCl and CaCl₂ (1 : 1 by weight) to nonsaline irrigation waters. Saline treatments with electrical conductivity (EC) of 4 dS m⁻¹ were compared with nonsaline controls (EC = 0.5 dS m⁻¹). Ion concentrations in leaves, stems, roots, and when present, pods were

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determined at four stages of growth: vegetative, flowering, podding, and grain filling. Both Na\(^+\) and Cl\(^-\) were excluded from the Manokin leaves and stems when plants were drip-irrigated and the uptake of these ions occurred solely via the root pathway. However, when saline water was applied by sprinkling, the ions entered leaves by both foliar absorption and root uptake and their concentrations in the leaves were about 9-fold higher than in those under saline drip irrigation. Regardless of treatment, leaf-K was highest during the vegetative stage, then decreased with plant age as K\(^+\) was mobilized to meet nutrient demands of the developing reproductive structures.

**Key Words:** Chloride; Drip irrigation; Foliar absorption; Ion exclusion; Sodium; Sprinkler irrigation.

**INTRODUCTION**

In addition to the detrimental effects of soil salinity imposed by drip or surface irrigation on root uptake of salts, crops that are sprinkled can accumulate ions in their leaves by direct foliar absorption.\(^1\) Sodium and Cl\(^-\)/C\(_0\) are readily absorbed through leaves at rates that are essentially linear functions of salt concentrations and time under treatment.\(^2,3\) The relative contributions of root- and foliar-absorption processes to foliar accumulation of salts have been reported for several crops.\(^4-7\)

In common with other natrophobic species in the Fabaceae, soybean responds to salinity by active exclusion of Na\(^+\) from the leaves. The primary mechanism is one in which Na\(^+\) transport to the leaves is limited by Na\(^+\) retention in the xylem parenchyma cells of the proximal root and basal portions of the stem.\(^8,9\) Sodium is progressively depleted from the xylem sap as it moves upward from the roots to stem tissue and finally to the leaves of soybean.\(^10\) A contributing mechanism for maintenance of low leaf-Na concentrations is the reabsorption of Na\(^+\) from the xylem in the shoot organs and its retranslocation basipetally in the phloem to the roots where it may be confined to the basal zone or may be secreted to the external medium.\(^11\) The efficiency of these exclusion processes varies among soybean cultivars.\(^9,10\)

Chloride exclusion from leaf tissue by retention in roots is also a feature of salt regulation by certain legumes, although the capacity of this process is relatively low compared to the mechanism that limits Na\(^+\) transport to the leaves.\(^9\) Chloride efflux from the leaf and retranlocation to the root appears to be a less effective means of Cl\(^-\) control than by retention in the roots.\(^11\) Salt tolerance of soybean has been positively correlated with chloride
exclusion from the leaves. Field trials have demonstrated wide varietal differences in response to high external Cl\(^-\) resulting either from irrigating with saline waters containing NaCl and CaCl\(_2\),\(^{[12]}\) by applying KCl fertilizers,\(^{[13]}\) or by amending the soil with CaCl\(_2\).\(^{[14]}\) All three studies showed that leaves of the salt sensitive cultivars were severely injured due to Cl-toxicity and contained 10 to 15 times more Cl\(^-\) than the tolerant, Cl-excluding varieties.

This study was conducted to determine the yield response of “Manokin” soybean to the application of saline water by above-canopy sprinkler and drip irrigation methods, and to compare ion partitioning and accumulation by the root pathway alone (e.g. drip irrigation) with the combination of foliar-plus root-absorption (e.g. sprinkler irrigation).

### MATERIALS AND METHODS

The study was conducted at the University of California Agricultural Experiment Station, Riverside, CA in four field plots measuring 27.4 by 36.6 m. Triple 15 NPK fertilizer was broadcast preplant on the plots at a rate of 366 kg ha\(^{-1}\). Experimental details are given in Wang et al.\(^{[15]}\) Briefly, drip irrigation systems were installed in two of the four plots, sprinkler systems in the other two. Soybean seeds (cultivar Manokin) were planted on 11 June 1998. To assure optimal stand establishment, seedlings in both the drip and sprinkler plots were irrigated for 41 DAP with good quality water (EC\(_i\) = 0.5 dS m\(^{-1}\)) containing (in mM): Na\(^+\) 1.7, K\(^+\) 0.06, Ca\(^{2+}\) 2.0, Cl\(^-\) 0.8. After this date, one plot of each irrigation treatment continued to receive nonsaline water and these two plots are designated Drip-Control and Sprinkler-Control, respectively. The remaining two plots, i.e., Drip-Salinity and Sprinkler-Salinity, were irrigated with water salinized with equal weights of NaCl and CaCl\(_2\) to give an EC\(_i\) of about 4 dS m\(^{-1}\). Irrigation frequencies and amounts were chosen to meet evapotranspiration needs of the two control plots, and exactly the same amount of saline water was applied to the corresponding salinity plots. At the end of each irrigation, the Sprinkler-Salinity plot was supplied with nonsaline water for 30 min to remove saline water from the sprinkler system.

On 39, 60, 81, and 102 DAP, three plants at each of three different locations were harvested from each salinity and irrigation treatment. These dates corresponded to vegetative (V6–7), flowering (R1), podding (R3), and grain filling stages (R5), as described by Fehr et al.\(^{[16]}\) Plants were separated into leaves, stems plus petioles, roots, and pods, when present. Samples were washed in deionized water to remove salts from the tissue surfaces, blotted dry, and
dried in a forced air oven at 70°C for 14 d. Organs from each set of three plants were combined to give three composite samples of leaves, stems, and roots, then ground in a Wiley mill to pass a 60-mesh screen. Calcium, Na⁺, and K⁺ were determined on nitric-perchloric acid digests of the plant material by inductively coupled plasma optical emission spectroscopy. Chloride was determined on nitric–acetic acid extracts by colorimetric–amperometric titration.

Statistical analyses of the ion data were performed by analysis of variance with mean comparisons at the 95% level based on Tukey’s studentized range test. SAS release version 6.12 was used. [17]

RESULTS AND DISCUSSION

Mineral analysis of Manokin seedlings sampled 39 DAP, two days prior to the imposition of the saline treatments, showed distinctly different Na⁺ and Cl⁻ uptake patterns that could be correlated with irrigation method (Fig. 1). Sodium concentrations were 6-fold higher in the leaves, and 4-fold higher in stems of plants under sprinkler irrigation compared to plants under drip irrigation. Sprinkling also resulted in significantly higher Cl⁻ in leaves, stems and roots than drip irrigation. Foliar absorption appeared to be a significant component of total Na⁺ and Cl⁻ accumulation in the entire seedling even under nonsaline conditions. Concentrations of both Na⁺ and Cl⁻ were also higher in the roots of the sprinkled plants possibly by the reabsorption of these ions from the xylem and their basipetal retranslocation to the roots. Calcium was significantly higher (16%) in leaves of the sprinkled plants than in those under drip irrigation, but stem- and root-Ca concentrations were unaffected by irrigation method.

Root-K in the sprinkled plants sampled 39 DAP was significantly lower (30%) than in the roots of plants under drip irrigation (Fig. 1), a difference that was not reflected in the above-ground organs. Potassium concentrations in Manokin leaves and stems were 575 and 700 mmol kg⁻¹, respectively, regardless of irrigation method. The values were typical for K⁺ accumulation and partitioning by K-sufficient soybean plants during the early vegetative stage of growth. [18]

Stem-Mg was slightly (13%), but significantly, higher in plants under drip irrigation than those sprinkled irrigated. Leaf- and root-Mg concentrations were not affected by irrigation method (data not presented).

The time course of Ca²⁺, Na⁺, Cl⁻, and K⁺ concentrations in soybean leaves is shown for drip (Fig. 2) and sprinkler (Fig. 3) irrigation. Leaves of the plants sampled during this period were free of visible symptoms of ion deficiencies or toxicities. Leaf-Ca increased with plant age and was not
Figure 1. Concentrations of Ca\(^{2+}\), Na\(^{+}\), Cl\(^{-}\), and K\(^{+}\) in soybean tissues under drip ■ and sprinkler □ irrigation. Seedlings were irrigated for 35 d after emergence with nonsaline water (EC\(_i\) = 0.5 dS m\(^{-1}\)). Values are the means of six replications ± SE.
Figure 2. Time-course of $\text{Ca}^{2+}$, $\text{Na}^+$, $\text{Cl}^-$, and $\text{K}^+$ accumulation in soybean leaves under drip irrigation with nonsaline water (○) or saline water (△). Key: ↓ initiation of saline treatment. Values are the means of three replications ± SE.
Figure 3. Time-course of Ca$^{2+}$, Na$^+$, Cl$^-$, and K$^+$ accumulation in soybean leaves under sprinkler irrigation with nonsaline water (○) or saline water (△). Key: ↓ initiation of saline treatment. Values are the means of three replications ±SE.
markedly influenced by the salt concentration in waters applied by drip irrigation. Over the season, leaves of plants sprinkled with saline waters accumulated more Ca$^{2+}$ than the controls and this effect was significant at 81 and 102 DAP. Sodium concentration in leaves of plants under drip irrigation averaged about 3 mmol kg$^{-1}$ over the 60 d sampling period regardless of salinity. Leaf-Na in the sprinkler plots was initially variable, averaging about 20 mmol kg$^{-1}$. On subsequent sampling dates, leaf-Na in the sprinkler-controls decreased and remained between 5 and 7 mmol kg$^{-1}$. The concentration of Na absorbed by leaves of many herbaceous crops appears to be a linear function of the duration of sprinkling.$[3]$ However, this response was not observed for Manokin soybean, as leaf-Na in the plants sprinkled with saline water increased to 25 mmol kg$^{-1}$ 81 DAP and was not significantly affected by additional sprinkling time (Fig. 3). Possibly a feedback system is present in this soybean cultivar whereby foliarly-absorbed Na$^+$ affects the uptake and concentration of Na$^+$ transported via the root pathway. Similar control mechanisms have been suggested for grape$[7]$ and barley.$[6]$ These research teams postulated that the influx of the monovalent ions (i.e., Na$^+$ and Cl$^-$) into the root may depend on and be controlled by the concentrations present in the leaf.

Leaf-Cl increased over time under drip irrigation, and leaves of the salinized plants contained about 30% more Cl$^-$ than the controls at each sampling date (Fig. 2). Leaf-Cl in the sprinkler-control plants was relatively constant with plant age, whereas the sprinkler-salinity treatment resulted a linear increase in leaf-Cl concentrations that was significantly higher than the sprinkler-controls (Fig. 3). No visible symptoms of Cl-toxicity were observed at any sampling date. Leaf scorch in soybean has been positively correlated with Cl$^-$ concentrations in leaves sampled at blossom appearance (stage R1, 60 DAP in the present study). Parker et al.$[13]$ found that damaged leaves of the Cl-accumulating cultivars contained $\sim 400$ mmol Cl$^-$ kg$^{-1}$, whereas cultivars classified as Cl-excluders showed no injury symptoms at any sampling date and averaged $\sim 37$ mmol Cl$^-$ kg$^{-1}$. Judged by this criterion, Manokin can be rated as a Cl-excluding soybean cultivar.

Numerous studies with a wide variety of crops have shown that K$^+$ concentration in plant tissues declines as Na-salinity in the root media increases.$[19]$ The effect is often more pronounced under sprinkler irrigation and the magnitude of the response varies widely with species$[3]$ or even cultivar.$[5]$ In the present study, however, K$^+$ concentration in soybean leaves (Figs. 2 and 3) as well as in stems and roots (data not presented) was highest early in the life cycle and then decreased over time, with only minor effects due to salinity or irrigation method. The plants were well into the reproductive stage by the last sampling date (102 DAP) and the pods represented a very strong sink for K$^+$. Declines in K$^+$ in soybean vegetative tissues with plant age
have been associated with K$^+$ mobilization and redistribution to developing reproductive structures.[18]

Ion partitioning in Manokin soybean harvested 102 DAP is shown in Fig. 4. Differences in soil salinity and irrigation method had little effect on leaf-Ca under control conditions (Fig. 4). However, leaves of the plants sprinkled with saline water accumulated significantly more Ca$^{2+}$ than those under drip irrigation, perhaps as a consequence of foliar absorption. Neither irrigation method nor salinity significantly influenced Ca$^{2+}$ in stems, roots or pods.

Salinity had no appreciable influence on leaf-Na concentration (3 mmol kg$^{-1}$) in drip-irrigated plants (Fig. 4). Sprinkling with nonsaline water resulted in a very slight, but significant, increase in leaf-Na compared to drip irrigation. Leaf-Na in the saline-sprinkler treatment was nearly 8-fold higher than in the saline-drip treatment, a result that was undoubtedly due to foliar absorption. The Na$^+$ distribution pattern in the plant parts illustrates a response to salinity that is characteristic of many leguminous species, i.e., Na$^+$ exclusion from the leaves by retention in roots, and to a more limited extent, stems.[9] Another process that contributes to the control of Na$^+$ accumulation in leaf tissue is the reabsorption and retranslocation of Na$^+$ to the roots. Root-Na in plants sprinkled with saline water was significantly higher than in the drip-irrigated plants, which suggests foliarly absorbed-Na may have been redirected from Manokin leaves to roots. Immature pods of plants under drip irrigation contained 2 mmol Na kg$^{-1}$ regardless of salinity treatment, whereas pod-Na was 8 and 50 mmol kg$^{-1}$ in the sprinkler controls and salinity treatments, respectively.

Under nonsaline drip irrigation, Cl$^-$ was lower in soybean stems (5 mmol kg$^{-1}$) than in leaves (19 mmol kg$^{-1}$) or roots (36 mmol kg$^{-1}$), and these values significantly increased as salinity in the irrigation water increased (Fig. 4). Chloride-relations in sprinkled plants clearly shows the contribution of Cl$^-$-foliar absorption. Under nonsaline conditions, leaf-Cl in the sprinkled plants was about twice as high as in those under drip irrigation, whereas Cl$^-$ in stems and roots was not significantly affected by irrigation method. The influence of foliar uptake on leaf-Cl was even more evident in the saline treatment as Cl$^-$ concentration in the sprinkled plants increased 10-fold over the leaf-Cl under saline drip irrigation. Pod-Cl in both drip and sprinkler control treatments and in the plants drip-irrigated with saline water was 5 mmol kg$^{-1}$; this concentration increased significantly in pods sprinkled with saline water.

At both salinity levels, K$^+$ concentrations in the leaves, stems, and roots of drip-irrigated plants tended to be higher than in sprinkled plants; this result was significant for leaf-K in the control treatment and root-K in both salt treatments (Fig. 4). Pod-K concentration was significantly higher under
Figure 4. Concentration of Ca\(^{2+}\), Na\(^{+}\), Cl\(^{-}\), and K\(^{+}\) in soybean tissues under drip ■ and sprinkler □ irrigation for 64 d. C = Control treatment, S = Saline treatment. Values are the means of three replications ± SE.
nonsaline conditions when the plants were sprinkle-irrigated, but the method of saline water application did not affect pod-K.

The salt tolerance of certain soybean cultivars, such as “Lee”, has been correlated with the ability to control root uptake and subsequent translocation of Cl\(^-\) and Na\(^+\) to shoots effectively enough to limit accumulation of these ions in the leaves.\(^8,12,20\) “Lee”, along with two other Cl-excluders, “Forrest” and “Centennial” were used as parental lines in the development of “Manokin” soybean.\(^21\) Inheritance of the capacity for Cl\(^-\) exclusion in soybean is controlled by a single gene pair.\(^22\) The results of our study indicate that those mechanisms of ion exclusion and partitioning which contribute to salt tolerance of “Lee” have been inherited by “Manokin”. These processes are effective in regulating Na\(^+\) and Cl\(^-\) accumulation in soybean leaves provided the ions enter the plant via the specialized cells and tissues of the root pathway. However, leaves of crops such as soybean, generally have had little contact with external ionic environments, and mechanisms for acquiring, controlling, or redistributing ions that penetrate the cuticle have not evolved during crop domestication. Foliar absorption, therefore, becomes the dominant process for the accumulation of potentially toxic ions when the crop is challenged by over-canopy application of saline irrigation waters.

ACKNOWLEDGMENTS

The authors are indebted to Donald A. Layfield for mineral ion analyses and to Phyllis Nash for statistical analysis. Terence Donovan, John Draper, and James Poss provided skilled technical assistance.

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